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RESEARCH IN SEISMOLOGY: EARTHQUAKE MAGNITUDES

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Saint Louis University

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This report describes research on the applicability of the m_b:M_s method to discriminate between small-magnitude earthquakes and explosions in Eurasia. The report presents a formula, valid on a world-wide basis, which enables the M_s threshold to be lowered to 2.8. When this formula was applied to the data from moderate- to high-yield Eurasian explosions, it was found that the m_b:M_s curve for those events is the same as for Nevada Test Site events. Data are presented for some presumed Eurasian earthquakes whose m_b:M_s values place them in the explosion population.

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RESEARCH IN SEISMOLOGY: EARTHQUAKE MAGNITUDES

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INTRODUCTION

The research described in this report is concerned with the m_b:M_s discriminant between earthquakes and underground explosions, principally as applied to small-magnitude events occurring in Eurasia. Several related problems are investigated, namely: 1) The development of an M_s formula which makes use of the amplitude of 20-sec period surface waves at short distances. This formula, when used in conjunction with data from the high-gain, long-period seismograph network, provides a low threshold for reliable M_s determination. 2) A determination of m_b:M_s values for Soviet explosions of intermediate to high yield. The resultant m_b:M_s curve is found to be identical to that obtained for Nevada Test Site events. 3) A search for shallow-depth Eurasian earthquakes which have explosion-like m_b:M_s values.

SURFACE-WAVE MAGNITUDE (M_s) FORMULA FOR DISTANCES LESS THAN 20°

The standard M_s formula

$$M_s = 3.30 + 1.66 \log \Delta\,(^\circ) + \log A/T \text{ (microns/sec)}, \qquad (1)$$

where T is approximately 20 sec, is not used for $\Delta < 20^\circ$ because: 1) from theoretical considerations it is not applicable at $\Delta < 20^\circ$ (Nuttli, 1973) and 2) the amplitudes of 20 sec period surface waves are small on conventional seismograms at these distances. The first limitation can be overcome by developing a formula appropriate to the distance range which applies for 20-sec period waves, and the second by the use of data from the high-gain, long-period seismograph stations. Previously, attempts to determine M_s for small events from the data of near stations used the amplitudes of shorter period surface waves (e.g. Evernden, et al, 1971; Basham, 1971; Marshall and Basham, 1972; Karnik et al, 1962; Nuttli, 1973). All of these formulas suffer to the extent that they are dependent on the upper-crustal geology, which varies regionally. Therefore the m_b:M_s relations for earthquakes and explosions derived from them differ with geographic region. However, we shall show that if m_b is determined from the amplitudes of 1-sec period P waves at distances greater than 20°, and if M_s is determined exclusively from the amplitudes of 20-sec period surface waves, then the m_b:M_s curve established for Nevada Test Site events by Evernden et al (1971) satisfies the m_b:M_s values for Soviet explosions in Novaya Zemlya, Kazakh and three different sites in the Ural Mountains.

Deviation of the Formula. The empirical curve of Gutenberg and Richter (1936), which they used to define the surface-wave magnitude, can be fitted by a theoretical attenuation curve for which the coefficient of absorption is 0.015 deg^{-1} (Nuttli, 1973). This curve is shown as the solid-line curve in Figure 1. Over the distance range $25^o \leq \Delta \leq 140^o$ the theoretical curve can be closely approximated by a straight line with slope -1.66 (see figure 1), which conforms with the standard M_s formula given previously as Eq. (1). A straight-line fit to the theoretical curve will have a different slope at the shorter distances, which from Figure 1 is shown to be -1.07 for $10^o \leq \Delta \leq 30^o$. Therefore, an equation for M_s using the amplitude of 20-sec period surface waves at the near distances, $10^o \leq \Delta \leq 30^o$, is

$$M_s = 4.16 + 1.07 \log \Delta (^o) + \log A/T \text{ (microns/sec)} \qquad (2)$$

where the constant 4.16 is determined by requiring that Eqs. (1) and (2) give identical M_s values for Δ between 25^o and 30^o.

In practice, the amplitude of the largest wave motion in the period range 17 sec to 23 sec is used, rather than the amplitude at exactly 20 sec.

Figure 2 is a reproduction of the vertical-component seismograms at EIL (Israel), QUE (Pakistan) and KBL (Afghanistan) for an earthquake in the western Caucusus of $M_s = 4.2$. The purpose of this figure is to show that 20-sec period surface waves are well developed and measurable at distances of about 10^o to 20^o for small to moderate size earthquakes.

Comparison with Other Formulas. Figures 3 to 7 compare M_s values obtained using the newly-derived Eq. (2) with those obtained using the Basham (1971), Marshall and Basham (1972) and Karnik et al (1962) formulas. The standard value of M_s is taken to be that obtained using the conventional formula (Eq. 1) for stations at distances of 30^o and greater. Figures 3 to 7 show that the Basham and Karnik et al formulas generally overestimate M_s, the former by 0.5 to 1.0 units and the latter by about 0.2 to 0.7 units. Both the Marshall-Basham and the newly-derived Eq. (2) give values much more consistent with those obtained from teleseismic distances; Figs. 3 and 6 show little preference between the two formulas, but Figs. 4, 5 and 7 suggest that Eq. (2) gives better results. A further significant advantage of Eq. (2) is that it can be applied on a global or world-wide basis, whereas for the Marshall-Basham formula one must have a set of tables of P functions versus period, one table for each geographic region. This requires an accurate knowledge of the crustal structure in all the regions.

M_S Threshold Values as a Function of Epicentral Distance.

Under ideal conditions of low-noise background, a 20-sec period surface wave with a 1 mm zero-to-peak seismogram amplitude can just barely be resolved. Accepting this as the minimum amplitude signal that can be read to determine M_S from the high-gain, long-period seismographs, we calculated the smallest M_S value that can be detected by these instruments, which are taken to have a magnification of 20,000 at 20-sec period. Eq. (1) was used for $\Delta \geq 30^\circ$ and Eq. (2) for $30^\circ \geq \Delta \geq 10^\circ$. The results are:

(deg)	Threshold M_S
10	2.6
15	2.8
20	2.9
25	3.1
30	3.2
40	3.4
50	3.5
75	3.8
100	4.0
130	4.2

The above values are the M_S thresholds for a single seismograph (not an array) with a magnification of 20,000 at 20-sec period, operating under quiet conditions so that a trace amplitude of 1 mm can be detected. In the present study we have been able to determine M_S values as low as 2.9, under favorable conditions.

m_b:M_S VALUES FOR SOVIET EXPLOSIONS

We have determined m_b:M_S values for all the Soviet explosions known to us for the interval August through December 1971. The dates, times and locations of the ten events, as taken from the NEIC bulletins, are given in Table 1. Five of the ten underground explosions were at the Eastern Kazakh site, but none of the remaining five were at the same location. Thus the data represent six source regions, separated very widely geographically.

m_b and M_S values determined by us, as well as by the National Earthquake Information Center (Boulder, Colorado), International Seismological Centre (Edinburgh, United Kingdom), Moscow (U.S.S.R.) and Hagfors Observatory (Sweden) are given in Table 2. No M_S value could be determined by us for the 19 Sept 1971 event because the surface waves of

an earthquake interfered with those of the explosion. We could not identify any surface waves from the explosions of 04 Oct 1971 and 22 Oct 1971, but from the background noise of the seismograms we determined that the M_s for each event could not have been any larger than 2.9, and may have been smaller.

Figure 8 is a plot of our m_b:M_s values for the Eurasian explosions. On the same figure is plotted an m_b:M_s curve for Nevada Test Site events, as given by Evernden et al (1971), where m_b was determined from teleseismic P waves and M_s from 20-sec period surface waves. A remarkable feature of Figure 8 is that the Soviet explosion data, from 5 widely scattered source locations, fit remarkably well with the NTS data over the entire range of intermediate- to high-yield events. This strongly suggests that the m_b:M_s relation for underground explosions is the same for all regions of the world, if m_b is determined from 1-sec teleseismic P waves and M_s from 20-sec surface waves. The regional dependence of m_b:M_s, as found by other investigators, most likely results from their use of an M_s formula which had built into it a regional bias. In other words, there is a question of the reliability of their M_s values for small events.

SHALLOW-DEPTH EURASIAN EARTHQUAKES

We have selected for study a fairly large and representative set of Eurasian earthquakes of m_b between approximately 4 and 5 that occurred from August through December 1971. We determined m_b and M_s for each of these earthquakes, with m_b obtained exclusively from 1-sec period teleseismic P-wave amplitudes and M_s exclusively from 20-sec surface-wave amplitudes. In addition to the data from the eight high-gain, long-period seismograph stations we used the seismograms from 20 standard WWSSN stations.

Table 2 summarizes our m_b:M_s studies for the Eurasian earthquakes and explosions in the interval August through December 1971. The results are also presented graphically in Figure 9.

In Figure 9 we can see that a curve (dashed line) displaced one-half m_b unit to the left of the NTS or Eurasian explosion curve will serve as an envelope to almost all the m_b:M_s values of the Eurasian earthquakes. There are three, and possibly four, exceptions to this statement. These are the presumed earthquakes of 16 August, 24 October, 4 December and 24 November 1971, which are identified by date in Figure 9.

From pP and sP phases we were able to establish that all four earthquakes had their focus in the crust, so that greater-than-normal focal depth cannot be called upon to explain the relatively small M_s values.

Although we have not made a detailed study of this point, it is our general impression that earthquakes in the interior of Eurasia more often have m_b:M_s values close to that of the dashed curve in Figure 9, whereas Pacific Coast earthquakes generally have a relatively large M_s value, which puts them to the left in Figure 9. We caution, however, that there likely will be exceptions to this statement.

CONCLUSIONS

The newly-derived formula (Eq. 2) for M_s, which is applicable on a world-wide basis and gives magnitudes which agree with those obtained by the conventional formula, enables one to lower the threshold of M_s down to about 2.8 when data from the high-gain, long-period seismographs are used. When the M_s values of Eurasian explosions are determined by use of this new formula, the m_b:M_s curve for intermediate to high-yield Eurasian explosions at five different sites is found to be identical to that for Nevada Test Site explosions.

All of the Eurasian earthquakes studied, with the exception of four, have an m_b value at least 0.5 units less than that of an underground explosion of the same M_s value, over the range of m_b from 4.0 to 5.6. Two definitely anomalous earthquakes (24 Oct and 04 Dec) had m_b:M_s values identical to those found for nuclear explosions. The earthquake of 16 Aug lies between the explosion and limiting earthquake curves. No surface waves could be identified for the third anomalous earthquake; the maximum possible value it could have, as determined from the background noise level, places it on the fringe of the earthquake population. A smaller value would place it in the explosion population. All of these anomalous earthquakes are shallow events.

REFERENCES

Basham, P. W. (1971). A new magnitude formula for short period continental Rayleigh waves, Geophysical Journal of the Royal Astronomical Society, 23, 255-260.

Evernden, J. F., W. J. Best, P. W. Pomeroy, T. V. McEvilly, J. M. Savino and L. R. Sykes (1971). Discrimination between small-magnitude earthquakes and explosions, Journal of Geophysical Research, 76, 8042-8055.

Karnik, V., N. V. Kondorskaya, Y. V. Riznichenko, E. F. Savarensky, S. L. Soloviev, N. V. Shebalin, J. Vanek and A. Zatopek (1962). Standardization of the earthquake magnitude scale, Studia Geophysica et Geodetica, 6, 41-47.

Marshall, P. D. and P. W. Basham (1972). Discrimination between earthquake and underground explosions employing an improved M_S scale, Geophysical Journal of the Royal Astronomical Society, 28, 431-458.

Nuttli, O. W. (1973). Seismic wave attenuation and magnitude relations for eastern North America, Journal of Geophysical Research, 78, 876-885.

TABLE 1. DATES, TIMES AND LOCATIONS OF SOVIET EXPLOSIONS STUDIED

Date	Origin Time	Lat.(^{o}N)	Long.(^{o}E)	Location
19-09-71	11-00-06.8	57.8	41.1	Western Russia
27-09-71	05-59-55.2	73.4	55.1	Novaya Zemlya
04-10-71	10-00-02.0	61.6	47.1	Western Russia
09-10-71	06-02-57.1	50.0	77.7	Eastern Kazakh
21-10-71	06-02-57.3	50.0	77.6	Eastern Kazakh
22-10-71	05-00-00.4	51.6	54.5	Western Russia
29-11-71	06-02-57.1	49.8	78.1	Eastern Kazakh
15-12-71	07-52-58.6	50.0	77.9	Eastern Kazakh
22-12-71	06-59-56.3	47.9	48.2	Western Russia
30-12-71	06-20-57.7	49.7	78.1	Eastern Kazakh

TABLE 2. MAGNITUDES AND LOCATIONS OF EVENTS STUDIED

Date[a]	Origin Time[b]	Lat. (^{o}N)[b]	Long.(^{o}E)[b]	Depth(km)[c]	mb[c]	M_s[c]
01-08-71	18-55-10.6	44.4	148.9	(33)-N (39)-I	4.3 (4.5)-N (4.5)-I	4.0
05-08-71	22-37-10.9	12.6	94.8	(31)-N (21)-I (110)-M	5.0 (5.0)-N (4.9)-I (4.5)-M	5.0
07-08-71	15-21-52.5	36.1	77.7	(33)-N (10)-I	4.5 (4.8)-N (4.9)-I (5.2)-M	4.2
08-08-71	02-42-20.5	8.2	58.4	(33)-N (179)-I	4.6 (5.1)-N (4.5)-I	4.4 (4.6)-M
09-08-71	01-03-16.6	42.1	83.4	(33)-N (33)-I	4.3 (4.2)-N	3.4
02-08-71	04-17-05.6	12.6	95.1	(40)-N (20)-I	5.1 (5.3)-N (5.3)-I (5.5)-M	5.0 (5.1)-N
12-08-71	20-57-57 7	49.7	156.0	(45)-N (42)-K	4.6 (4.5)-N (4.6)-I (5.1)-M	4.2
15-08-71	12-14-29.3	21.9	121.8	(28)-N (19)-I	5.2 (4.8)-N (5.0)-I	4.7 (5.0)-M
16-08-71	04-58-00.3	28.9	103.7	(33)-N (32)-I	5.7 (5.5)-N (5.5)-I (5.6)-M	4.8
16-08-71	13-29-24.8	28.8	103.7	(33)-N (61)-I	4.8 (4.8)-N (4.8)-I (5.0)-M	4.0

TABLE 2 (Cont'd)

Date[a]	Origin Time[b]	Lat. (°N)[b]	Long. (°E)[b]	Depth(km)[c]	m_b[c]	M_s[c]
16-08-71	18-53-54.7	28.9	103.7	17 (33)-N (64)-I	5.4 (5.3)-N (5.3)-I (5.6)-M	5.4 (5.6)-N
16-08-71	22-37-33.6	28.8	103.6	13 (33)-N (25)-I (20)-M	5.3 (5.4)-N (5.3)-I	4.7 (5.1)-M
17-08-71	04-29-33.1	37.1	36.8	(33)-N (35)-I	4.8 (5.0)-N (5.0)-I	4.4 (4.6)-M
17-08-71	17-07-40.4	28.9	103.7	(33)-N (88)-I	4.9 (4.9)-N (4.7)-I	4.2 (4.8)-M
19-08-71	11-12-40.7	21.9	121.8	(15)-N (11)-I	5.0 (4.8)-N (4.9)-I (5.3)-M	4.9
20-08-71	19-06-28.6	61.8	5.0	(35)-N (35)-I	4.6 (4.5)-N (4.2)-I	3.8
21-08-71	19-34-23.2	81.9	118.9	(33)-N (84)-I	4.4 (4.6)-N (4.5)-I (4.7)-M	4.4
22-08-71	17-54-14.6	30.1	50.7	(33)-N (51)-I (20)-M	4.8 (5.1)-N (4.9)-I	4.5 (5.1)-M
24-08-71	09-52-52.0	45.3	151.3	(33)-N (40)-I	4.8 (4.7)-N (4.7)-I (5.5)-M	4.0
24-08-71	16-33-22.7	52.2	91.4	(33)-N (12)-I (20)-M	4.6 (5.2)-N (5.4)-I (5.7)-M (5.8)-H	5.0 (5.6)-M (5.5)-H

TABLE 2 (Cont'd)

Date[a]	Origin Time[a]	Lat. (^{o}N)[b]	Long. (^{o}E)[b]	Depth(km)[c]	m_b[c]	M_s[c]
25-08-71	00-30-44.5	28.2	52.3	(33)-N (43)-I	-[d] (4.1)-N	3.7
25-08-71	18-08-44.6	28.4	128.1	(40)-N (21)-I	4.5 (4.4)-N (4.4)-I (4.8)-M	4.1
26-08-71	06-55-08.7	30.0	50.7	(45)-N (42)-I	4.3 (4.8)-N (4.7)-I	4.4 (4.7)-M
26-08-71	11-55-51.0	44.5	9.6	(33)-N (33)-I	-[e] (4.0)-N	-[e]
28-08-71	16-34-44.4	37.6	55.8	(33)-N (33)-I	4.7 (4.8)-N (4.8)-I (4.7)-M (4.9)-H	4.0 (4.5)-M
29-08-71	15-16-56.9	36.5	78.5	(33)-N (101)-I	3.8 (5.0)-N	3.0 (4.4)-M
01-09-71	10-54-04.6	48.4	154.9	(50)-N (50)-I	4.8 (4.9)-N (4.9)-I	3.8
02-09-71	12-24-22.8	30.5	50.3	(33)-N (61)-I	4.8 (4.8)-N (4.8)-I	4.1 (4.3)-M
03-09-71	18-42-16.0	28.9	103.7	15 (33)-N (110)-I	4.7 4.8(N) 4.7(I)	3.3
03-09-71	21-33-08.5	48.2	6.5	(26)-N (26)-I	4.3	< 3.6[f]
04-09-71	01-10-33.0	29.0	103.7	(33)-N (97)-I	4.9 (5.0)-N (4.7)-I (4.6)-M	3.8

TABLE 2 (Cont'd)

Date[a]	Origin Time[b]	Lat. (°N)[b]	Long. (°E)[b]	Depth(km)[c]	m_b[c]	M_s[c]
05-09-71	14-55-21.0	56.0	165.1	(33)-N (26)-I (25)-M	5.0 (5.1)-N (5.1)-I	4.8 (4.9)-N (5.2)-M
06-09-71	00-33-25.9	33.2	69.9	(37)-N (26)-I	5.2 (4.9)-N (5.0)-I	4.5 (5.2)-M
06-09-71	04-21-43.9	46.8	141.4	(26)-N (16)-I	4.7 (4.8)-N (4.7)-I	3.8
07-09-71	04-02-24.2	46.1	12.4	(25)-N (28)-I	4.1 (4.2)-N (4.1)-I	3.2
07-09-71	07-54-28.7	43.2	0.2	(33)-N (33)-I	4.1 (4.0)-N	<3.3[f]
07-09-71	15-28-32.8	24.0	123.2	(33)-N (49)-I	4.6 (4.6)-N	3.9
08-09-71	22-35-15.8	41.1	43.8	(33)-N (33)-I	4.8 (4.8)-N (4.8)-I (5.0)-M (5.3)-H	4.2 (4.6)-M (4.3)-H
09-09-71	06-51-08.8	38.2	20.1	(5)-N (3)-I	4.3 4.3(N) 4.4(I)	3.0
09-09-71	21-06-20.1	46.6	140.9	(33)-N (10)-I	4.5 (4.5)-N (4.5)-I	4.4
11-09-71	02-03-09.9	38.9	22.1	(4)-N (5)-I	4.5 (4.5)-N (4.5)-I	3.8
11-09-71	06-28-11.1	15.1	96.3	(28)-N (30)-I	5.0 (5.3)-N (5.0)-I (5.4)-M	4.4

TABLE 2 (Cont'd)

Date[a]	Origin Time[b]	Lat. (^{o}N)[b]	Long. (^{o}N)[b]	Depth(km)[c]	m_b[c]	M_s[c]
14-09-71	03-11-04.3	22.9	100.8	(33)-N (42)-I	5.3 (5.4)-N (5.3)-I	5.4
14-09-71	06-56-31.8	42.4	144.7	(39)-N (54)-I	4.9 (4.9)-N (4.9)-I (5.1)-M	5.0
19-09-71 E	11-00-06.8	57.8	41.1	(33)-N (33)-I	4.4 (4.5)-N (4.5)-I (5.3)-H	-[g]
21-09-71	09-13-51.5	32.4	91.8	(33)-N (34)-I	4.8 (5.0)-N (4.6)-I	4.7
25-09-71	10-34-04.3	44.2	8.6	(19)-N (3)-N	4.4 (4.1)-N (4.0)-I	3.5
27-09-71 E	05-59-55.2	73.4	55.1	(0)-N (0)-I	6.2 (6.4)-N (6.5)-I (>6.4)-H	5.1 (5.2)-N (5.6)-H
28-09-71	14-13-09.3	40.2	143.4	(45)-N (26)-I	4.8 (4.2)-N (4.6)-I	4.5
29-09-71	07-18-51.6	47.1	9.0	(24)-N (24)-I	4.4 (4.5)-N (4.4)-I	3.7
29-09-71	15-47-58.3	55.4	163.6	(33)-N (0)-I	5.0 (5.0)-N (5.2)-I	4.1
01-10-71	16-27-47.7	38.6	69.8	(36)-N (21)-I (10)-M	4.8 (4.9)-N (4.9)-I (5.1)-M (4.9)-H	4.1 (4.4)-H
03-10-71	18-38-22.0	41.5	142.4	(48)-N (45)-I	4.1 (4.1)-N (4.2)-I	3.6
04-10-71 E	10-00-02.0	61.6	47.1	(13)-N (13)-I	4.5 (5.1)-N (4.6)-I (4.9)-H	<2.8[f]

TABLE 2 (Cont'd)

Date[a]	Origin Time[b]	Lat. (°N)[b]	Long. (°E)[b]	Depth(km)[c]	m_b[c]	M_s[c]
04-10-71	16-43-31.8	42.9	13.1	(33)-N (33)-I	4.6 (5.0)-N (4.5)-I (5.1)-M	4.1
04-10-71	22-21-57.2	43.1	12.9	(43)-N (43)-I	4.4 (4.4)-N	3.2
05-10-71	18-31-17.7	27.2	55.8	(39)-N (44)-I	5.0 (5.1)-N (5.1)-I (4.9)-M	4.1
06-10-71	01-46-38.3	38.3	30.2	(19)-N (19)-I	4.5 (4.6)-N (4.4)-I	3.9 (4.1)-M
09-10-71 E	06-02-57.1	50.0	77.7	(0)-N (0)-I	5.2 (5.4)-N (5.3)-I (5.8)-H	3.2
10-10-71	18-25-14.6	23.0	96.0	(33)-N (46)-I	5.1 (5.1)-N (4.9)-I	5.2 (5.3)-M
12-10-71	11-44-42.2	44.5	11.0	(25)-N (9)-I	–[h] (4.6)-N	–[h]
12-10-71	16-45-35.0	52.6	174.2	(29)-N	4.7 (4.4)-N	3.4
15-10-71	14-19-31.6	37.3	54.6	(39)-N (41)-I (25)-M	4.5 (4.7)-N (4.6)-I (5.0)-M (5.3)-H	3.8 (4.0)-M (3.8)-H
15-10-71	17-08-06.3	41.4	48.6	(33)-N (54)-I	4.9 (4.9)-N (4.8)-I (5.0)-M (5.2)-H	3.7 (3.5)-H

TABLE 2 (Cont'd)

Date[a]	Origin Time[b]	Lat. (°N)[b]	Long. (°E)[b]	Depth(km)[c]	m_b[c]	M_s[c]
20-10-71	08-40-19.0	21.9	121.4	(35)-N (42)-I (35)-M	5.6 (5.5)-N (5.6)-I (5.9)-M	5.3 (5.3)-N
21-10-71E	06-02-57.3	50.0	77.6	(0)-N (0)-I	5.5 (5.6)-N (5.5)-I (5.7)-H	3.5 (3.5)-H
22-10-71E	05-00-00.4	51.6	54.5	(6)-N (6)-I	5.2 (5.3)-N (5.2)-I (5.8)-H	< 2.8[f] (3.3)-H
24-10-71	08-59-04.6	28.2	87.2	20 (44)-N (57)-I	4.8 (5.1)-N (4.8)-I (5.0)-M	2.9
28-10-71	13-30-57.1	41.9	72.4	(22)-N (15)-I	5.3 (5.5)-N (5.4)-I (5.7)-M (5.3)-H	4.9 (5.2)-H
29-10-71	17-16-52.1	34.1	86.3	(33)-N (6)-I	4.7 (5.0)-N (4.9)-I	4.2 (4.7)-M
30-10-71	20-48-48.0	23.0	121.4	(35)-N (47)-I	5.3 (5.3)-N (5.3)-I (5.6)-M	5.3 (5.5)-N
31-10-71	15-54-47.9	26.2	90.7	(33)-N (33)-I	4.1 (4.6)-N (4.7)-I	3.2
01-11-71	05-29-57.2	44.0	85.0	(33)-N (30)-I (30)-M	4.9 (5.0)-N (5.0)-I (5.2)-M	4.7
03-11-71	09-42-50.4	28.3	57.0	(33)-N (102)-I	4.5 (4.7)-N (4.7)-I (4.9)-M	4.0
04-11-71	20-12-20.5	28.8	103.7	(34)-N (43)-I	4.9 (5.0)-N (4.9)-I (4.7)-M	3.9

TABLE (Cont'd)

Date[a]	Origin Time[b]	Lat. (^{o}N)[b]	Long.(^{o}E)[b]	Depth(km)[c]	m_b[c]	M_s[c]
05-11-71	14-55-48.8	24.7	63.3	(33)-N (50)-I (50)-M	4.7 (5.1)-N (4.9)-I (5.0)-M	4.1
08-11-71	23-24-43.8	63.0	5.1	(33)-N (33)-I	4.2 (4.5)-N	3.8
11-11-71	04-40-56.7	21.4	93.9	(48)-N (55)-I	4.9 (4.8)-N (5.0)-I (5.5)-M	4.0
13-11-71	15-47-41.5	11.0	39.7	(24)-N (39)-I (15)-M	5.2 (5.3)-N (5.1)-I (5.6)-M	4.9
18-11-71	07-31-32.8	38.3	66.8	(30)-N (27)-I (40)-M	5.3 (5.3)-N (5.2)-I (5.6)-M (5.5)-H	5.0 5.4(M) 5.3(H)
19-11-71	01-00-01.0	41.9	72.4	(33)-N (39)-I	4.9 (4.9)-N (4.9)-I (4.9)-M (5.0)-H	4.1 (4.9)-M (4.4)-H
23-11-71	17-40-05.8	28.8	103.7	(33)-N (33)-I	4.8 (4.8)-N (4.8)-I	3.4
24-11-71	08-23-24.6	38.7	73.3	40 (33)-N (95)-I (110)-M	4.6 (5.1)-N (4.8)-M (5.1)-H	2.9
29-11-71E	06-02-57.1	49.8	78.1	(0)-N (0)-I	5.4 (5.5)-N (5.4)-I (5.7)-H	3.8
04-12-71	08-38-00.7	27.9	87.9	(32)-N (29)-I	4.9 (5.0)-N (5.2)-I (5.4)-M	3.2

TABLE 2 (Cont'd)

Date[a]	Origin Time[b]	Lat. (°N)[b]	Long. (°E)[b]	Depth(km)[c]	m_b[c]	M_s[c]
07-12-71	22-34-14.7	35.8	67.7	(43)-N (34)-I	4.6 (4.3)-N (4.3)-M	3.9
12-12-71	13-41-39.8	41.4	79.2	(33)-N (21)-I	4.7 (4.7)-N (4.7)-I (4.9)-H	3.5 (4.1)-M (3.7)-H
12-12-71	22-27-41.1	39.5	73.2	(33)-N (33)-I (20)-M	4.9 (4.8)-N (4.5)-M (4.6)-H	3.7 (4.4)-M (4.6)-H
15-12-71 E	07-52-58.6	50.0	77.9	(0)-N (0)-I	5.0 (4.9)-N (4.9)-I (5.0)-H	3.3
16-12-71	00-03-06.3	55.7	164.0	(41)-N (28)-I	4.9 (4.8)-N (4.8)-I (4.8)-M	4.8
16-12-71	18-35-45.5	77.9	17.8	(33)-N (33)-I	5.0 (5.0)-N (4.9)-I (5.1)-M	4.8 (4.9)-N
19-12-71	07-50-27.8	55.9	163.1	(33)-N (7)-I	5.1 (5.0)-N (5.0)-I (5.7)-M	5.2 (5.3)-N
20-12-71	01-29-18.5	41.2	48.3	(33)-N (2)-I (15)-M	5.3 (5.0)-N (5.1)-I (5.5)-M (5.4)-H	5.2 (5.3)-M (5.0)-H
20-12-71	01-41-04.9	41.1	48.4	(33)-N (28)-I	5.2 (5.2)-N (5.1)-I (5.4)-M (5.8)-H	5.1 (5.2)-N (5.2)-M (5.3)-H

TABLE 2 (Cont'd)

Date[a]	Origin Time[b]	Lat. (°N)[b]	Long. (°E)[b]	Deptn(km)[c]	m_b[c]	M_s[c]
20-12-71	05-05-24.0	41.1	48.2	(33)-N (27)-I (15)-M	3.6 (4.5)-N (4.9)-M (4.9)-H	3.1 (4.0)-M
20-12-71	07-53-11.4	41.2	48.3	(33)-N (4)-I	5.0 (4.8)-N (4.8)-I (4.8)-M (4.8)-H	4.1 (4.7)-M (4.3)-H
20-12-71	16-23-25.9	55.8	163.6	(33)-N (2)-I (35)-M	4.9 (4.5)-N (4.5)-I (5.1)-M	4.7 (4.8)-N
20-12-71	21-42-00.4	55.5	162.9	(33)-N (85)-I	4.6 (4.4)-N (4.3)-I (4.0)-M	4.1
22-12-71 E	06-59-56.3	47.9	48.2	(0)-N (0)-I	5.8 (6.0)-N (6.0)-I (6.7)-H	4.2 (4.3)-H
23-12-71	01-11-43.7	56.0	163.7	(13)-N (24)-I	5.1 (4.8)-N (4.7)-I (4.3)-M	4.1
27-12-71	00-18-34.2	46.5	142.2	(39)-N (3)-I	4.9 (4.5)-N (4.5)-I (4.9)-M	4.0
27-12-71	20-59-34.1	35.1	73.1	(10)-N (55)-I	4.8 (5.4)-N (5.2)-I (4.5)-M	3.6
28-12-71	19-35-55.5	55.8	163.9	(33)-N (27)-I	5.0 (5.0)-N (4.9)-I (4.6)-M	4.1
29-12-71	09-41-51.7	55.2	164.5	(35)-N (13)-I	5.0 (5.0)-N (4.9)-I	3.9

TABLE 2 (Cont'd)

Date[a]	Origin Time[b]	Lat. (°N)[b]	Long. (°E)[b]	Depth(km)[c]	m_b[c]	M_s[c]
29-12-71	22-27-02.0	25.1	94.7	(33)-N (46)-I (60)-M	5.5 (5.5)-N (5.6)-I	5.0 (5.6)-M
30-12-71E	06-20-57.7	49.7	78.1	(0)-N (0)-I	5.5 (5.8)-N (5.7)-I	3.9

a An "E" after the date indicates a presumed underground explosion.

b The values given were determined by the National Earthquake Information Center (NEIC), Boulder, colorado.

c The values not enclosed in parentheses were determined in the present study. Those in parentheses and indicated N, I, M or H were determined by the NEIC, International Seismological Center (ISC), Moscow, U.S.S.R. and Hagfors Observatory, Sweden, respectively.

d The P-wave amplitudes were too small to allow us to determine m_b.

e The P-wave and surface-wave amplitudes were very small, and possibly interfered with by waves from another earthquake.

f The P waves and/or surface waves were too small to determine their amplitudes. The values for m_b and/or M_s given are upper limits, determined from the background microseismic level on the seismograms.

g The surface waves are interfered with by those of an earthquake, so that M_s could not be determined for this explosion.

h The m_b determination by NEIC apparently made use of waves of another event. The actual m_b and M_s of this earthquake were too small to determine from the data available to us. However, the data we have indicate that m_b was less than 3.8.

Figure Captions

Figure 1. Theoretical attenuation curve and magnitude formulas for 20-sec period surface waves.

Figure 2. Seismograms showing 20-sec period waves at small distances.

Figure 3. Surface wave magnitudes for earthquake of 27 September 1971. The X's are M_s values obtained from the conventional formula (eq. 1), the solid triangles from the formula presented in this report (eq. 2), the pluses from the formula of Marshall and Basham (1972), the rectangles from the formula of Karnik et al (1962), and the circles from the formula of Basham (1971).

Figure 4. Surface wave magnitudes for earthquake of 21 September 1971. The symbols are the same as in Figure 3.

Figure 5. Surface wave magnitudes for earthquake of 8 September 1971. The symbols are the same as in Figure 3.

Figure 6. Surface wave magnitudes for earthquake of 4 September 1971. The symbols are the same as in Figure 3.

Figure 7. Surface wave magnitudes for earthquake of 3 September 1971. The symbols are the same as in Figure 3.

Figure 8. $m_b{:}M_s$ values for Eurasian explosions. The solid-line curve is for Nevada Test Site events.

Figure 9. $m_s{:}M_b$ values for Eurasian earthquakes. The dashed-line curve, obtained by displacing the explosion curve by 0.5 m_b units, is an envelope for most of the earthquakes.

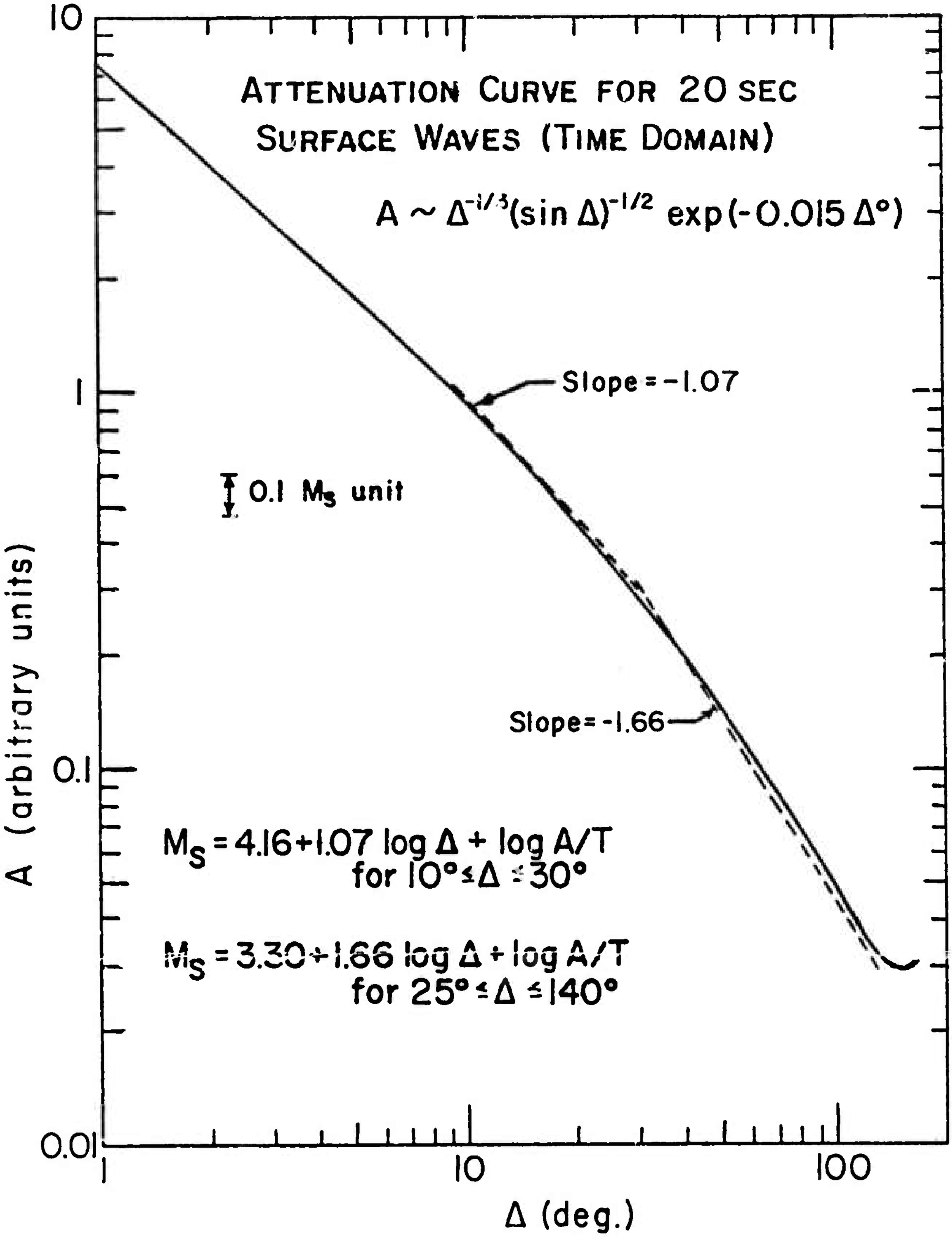

Figure 1. Theoretical attenuation curve and magnitude formulas for 20-sec period surface waves.

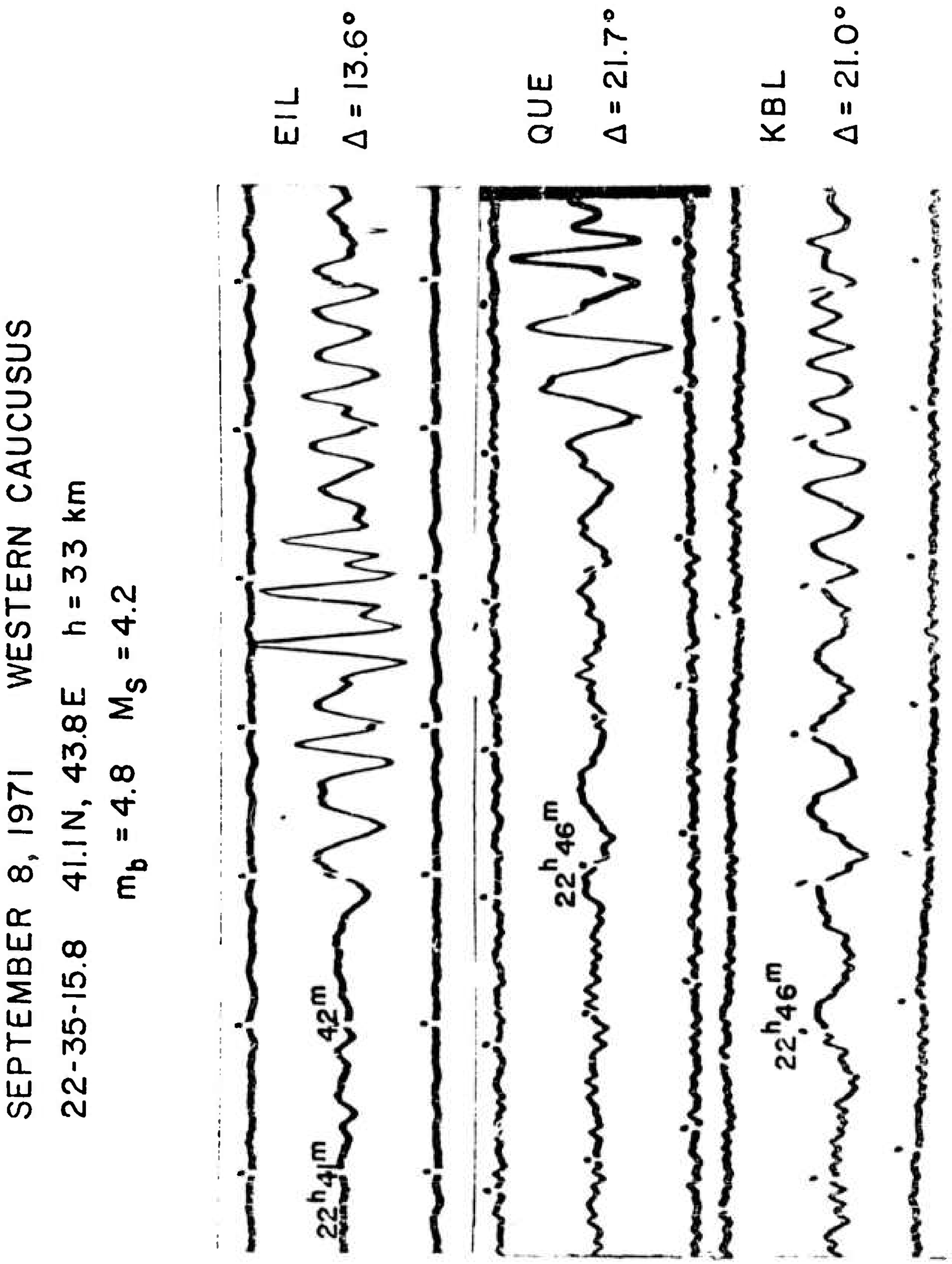

Figure 2. Seismograms showing 20-sec period waves at small distances.

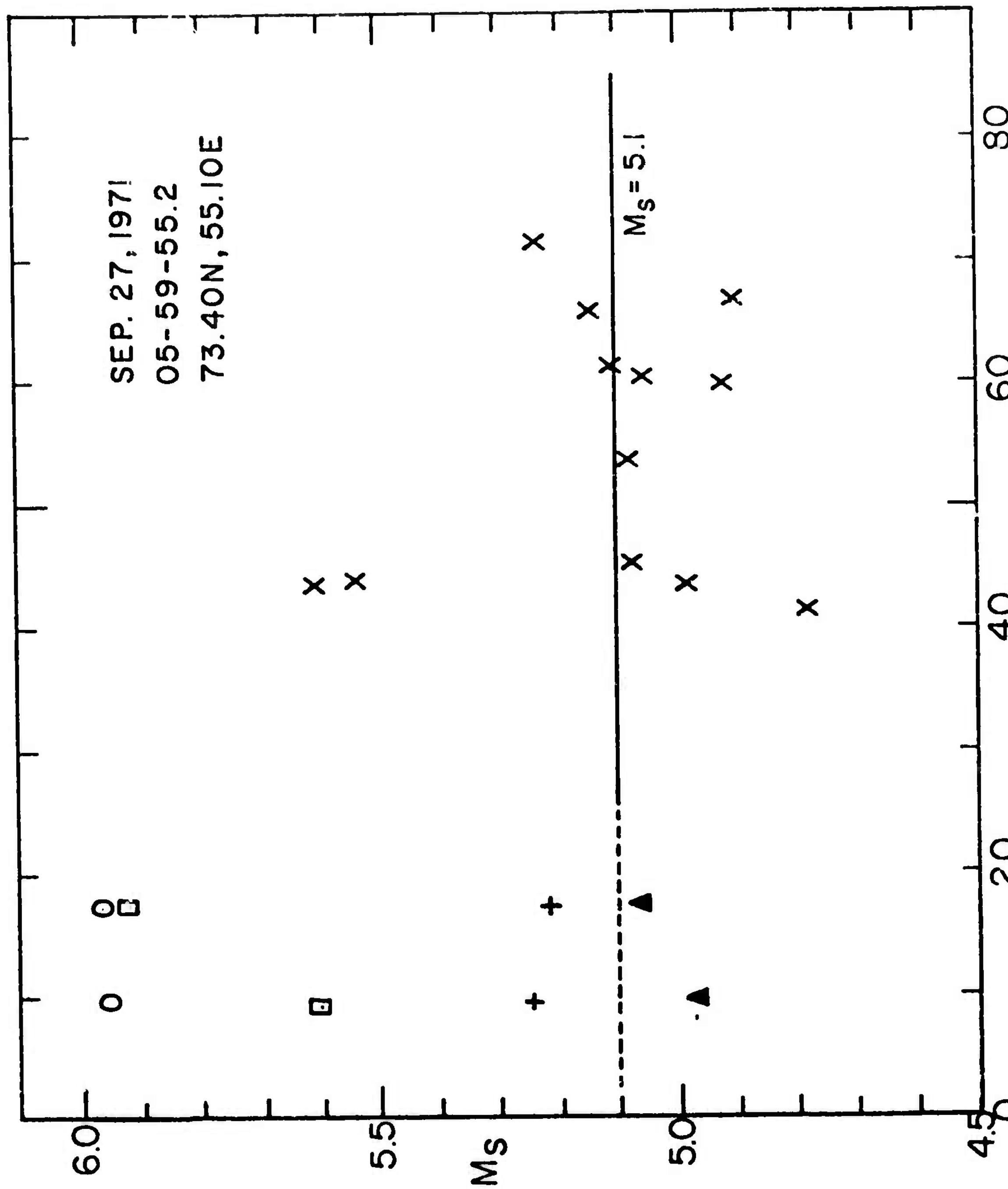

Figure 3. Surface wave magnitudes for earthquake of 27 September 1971. The X's are M_s values obtained from the conventional formula (eq. 1), the solid triangles from the formula presented in this report (eq. 2), the pluses from the formula of Marshall and Basham (1972), the rectangles from the formula of Karnik et al (1962), and the circles from the formula of Basham (1971).

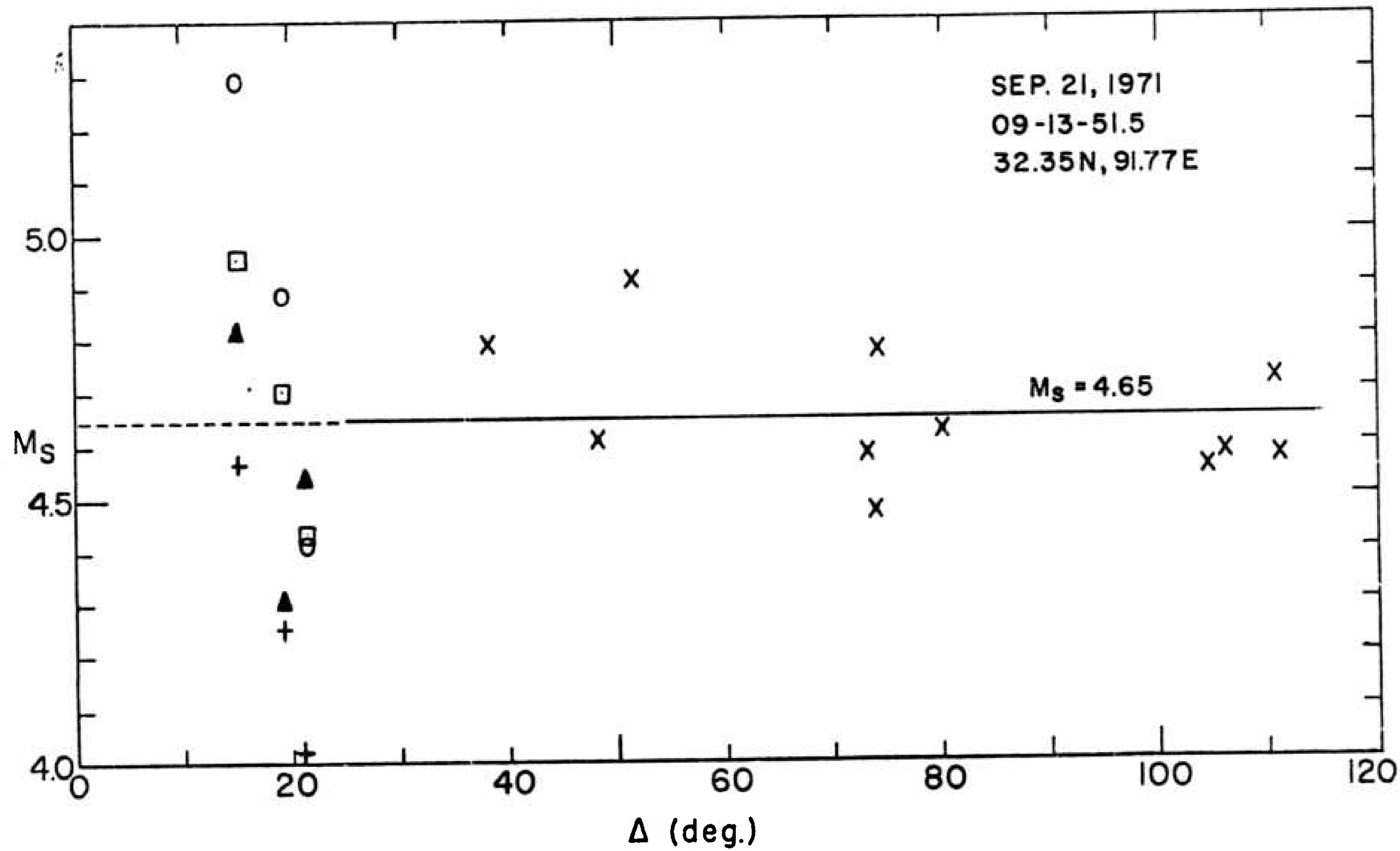

Figure 4. Surface wave magnitudes for earthquake of 21 September 1971. The symbols are the same as in Figure 3.

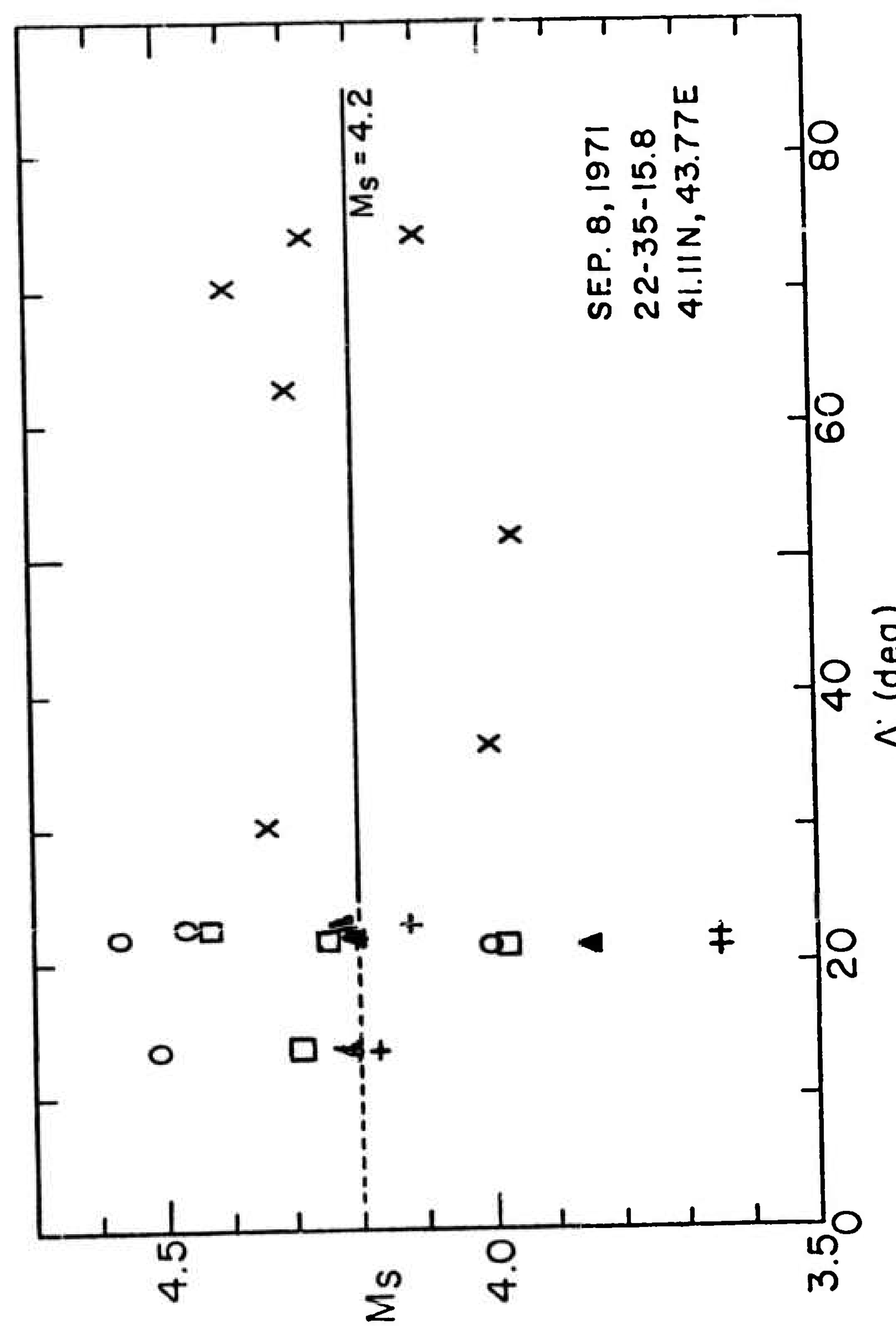

Figure 5. Surface wave magnitudes for earthquake of 8 September 1971. The symbols are the same as in Figure 3.

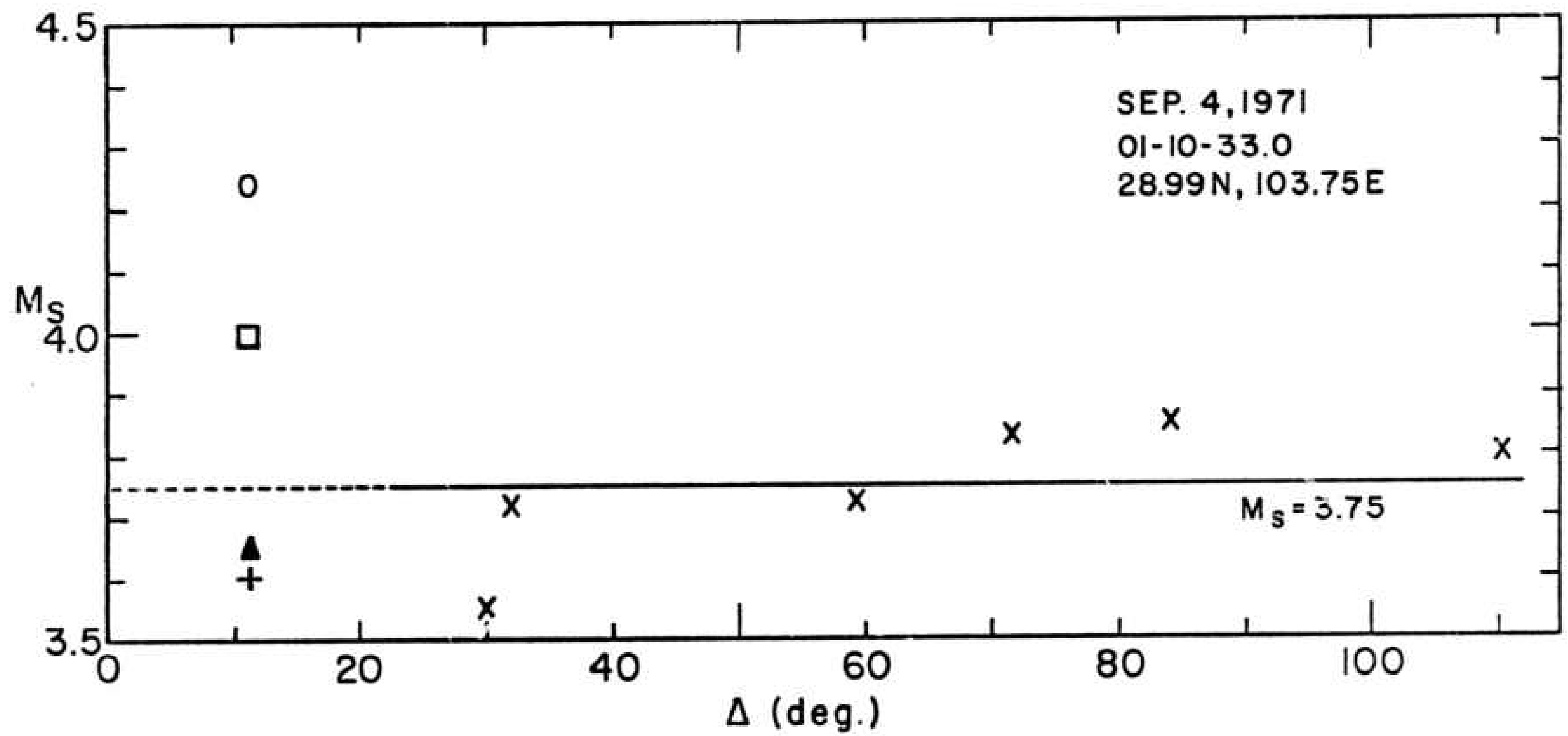

Figure 6. Surface wave magnitudes for earthquake of 4 September 1971. The symbols are the same as in Figure ˆ.

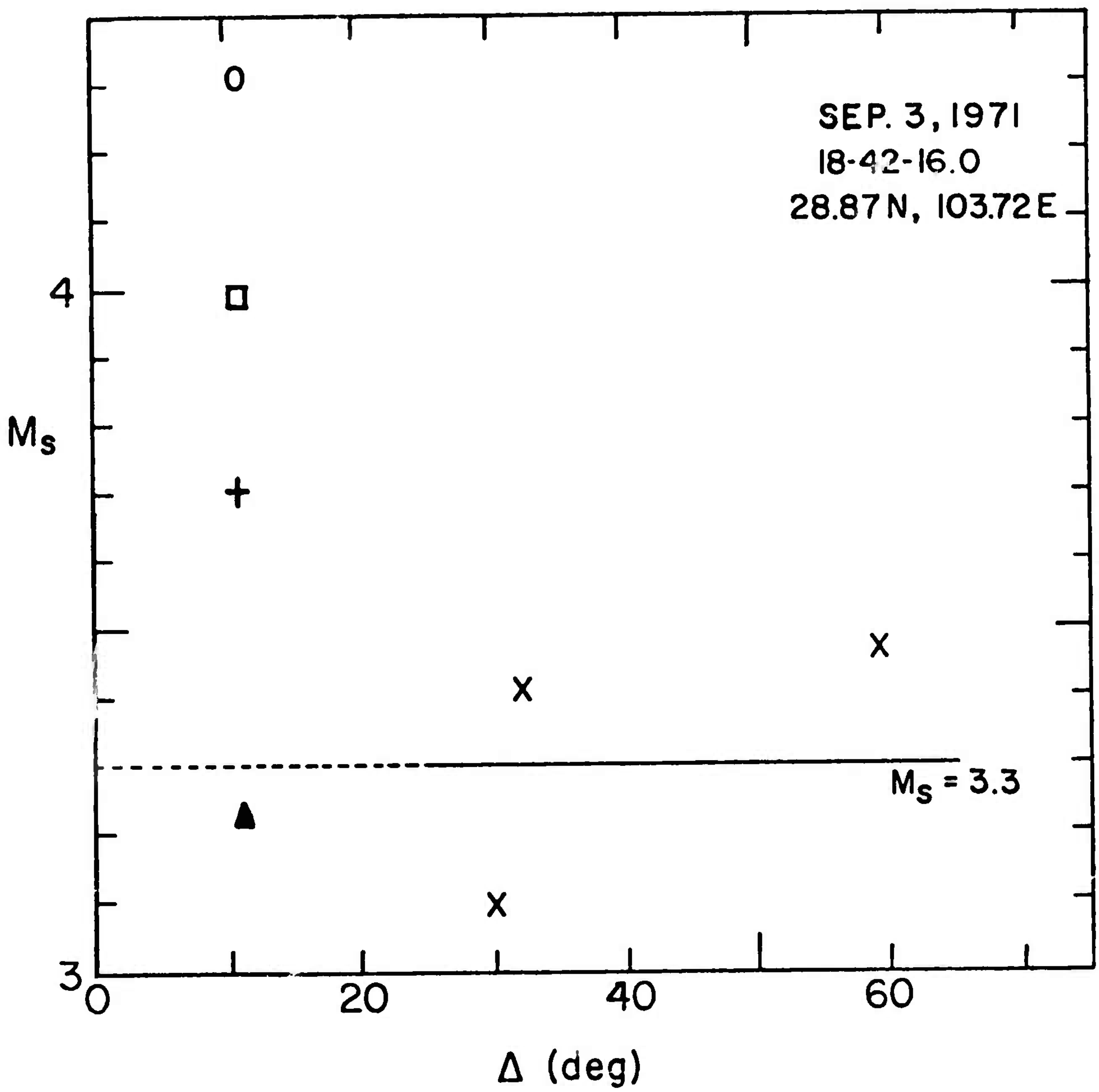

Figure 7. Surface wave magnitudes for earthquake of 3 September 1971. The symbols are the same as in Figure 3.

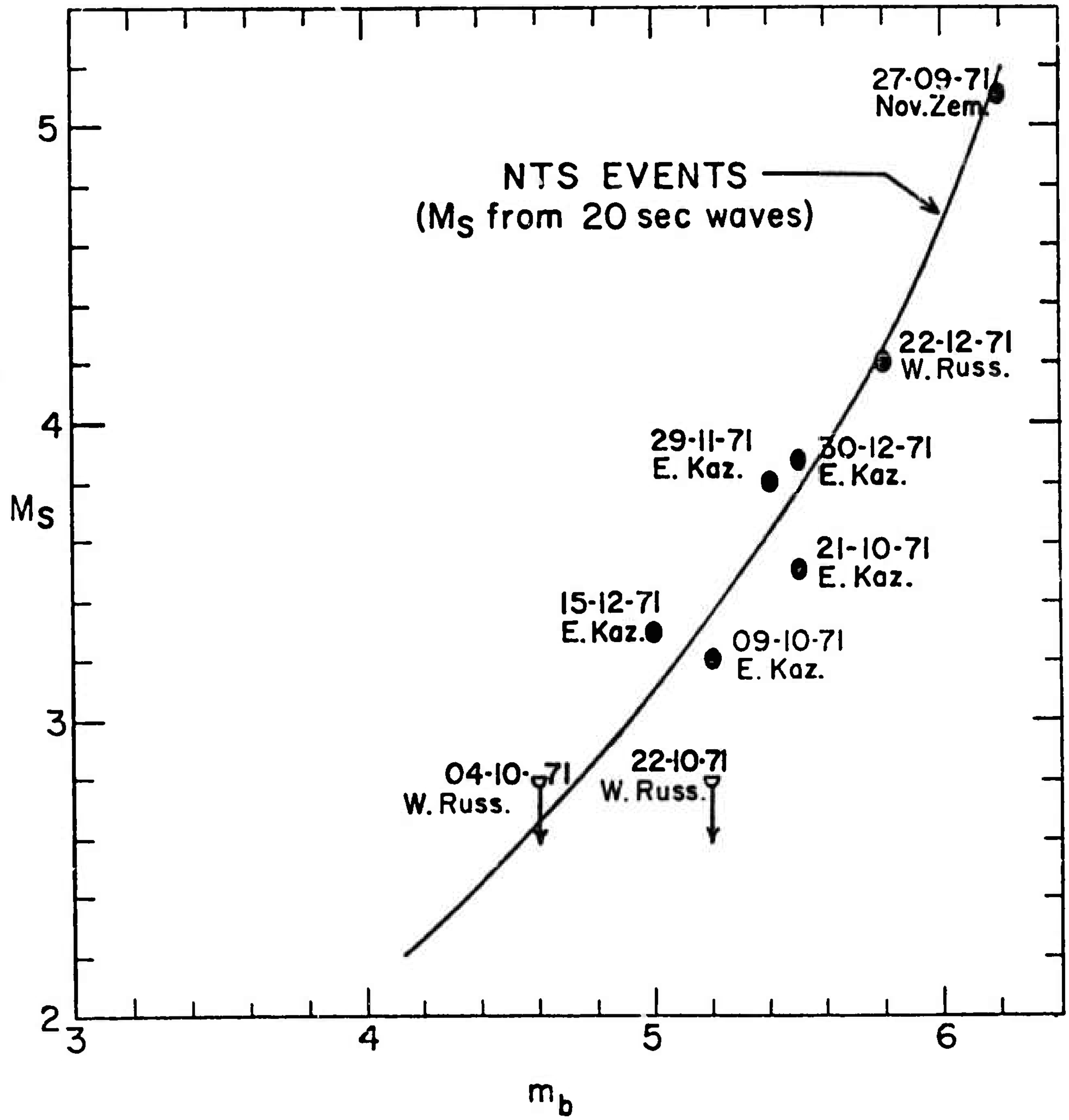

Figure 8. m_b:M_s values for Eurasian explosions. The solid-line curve is for Nevada Test Site events.

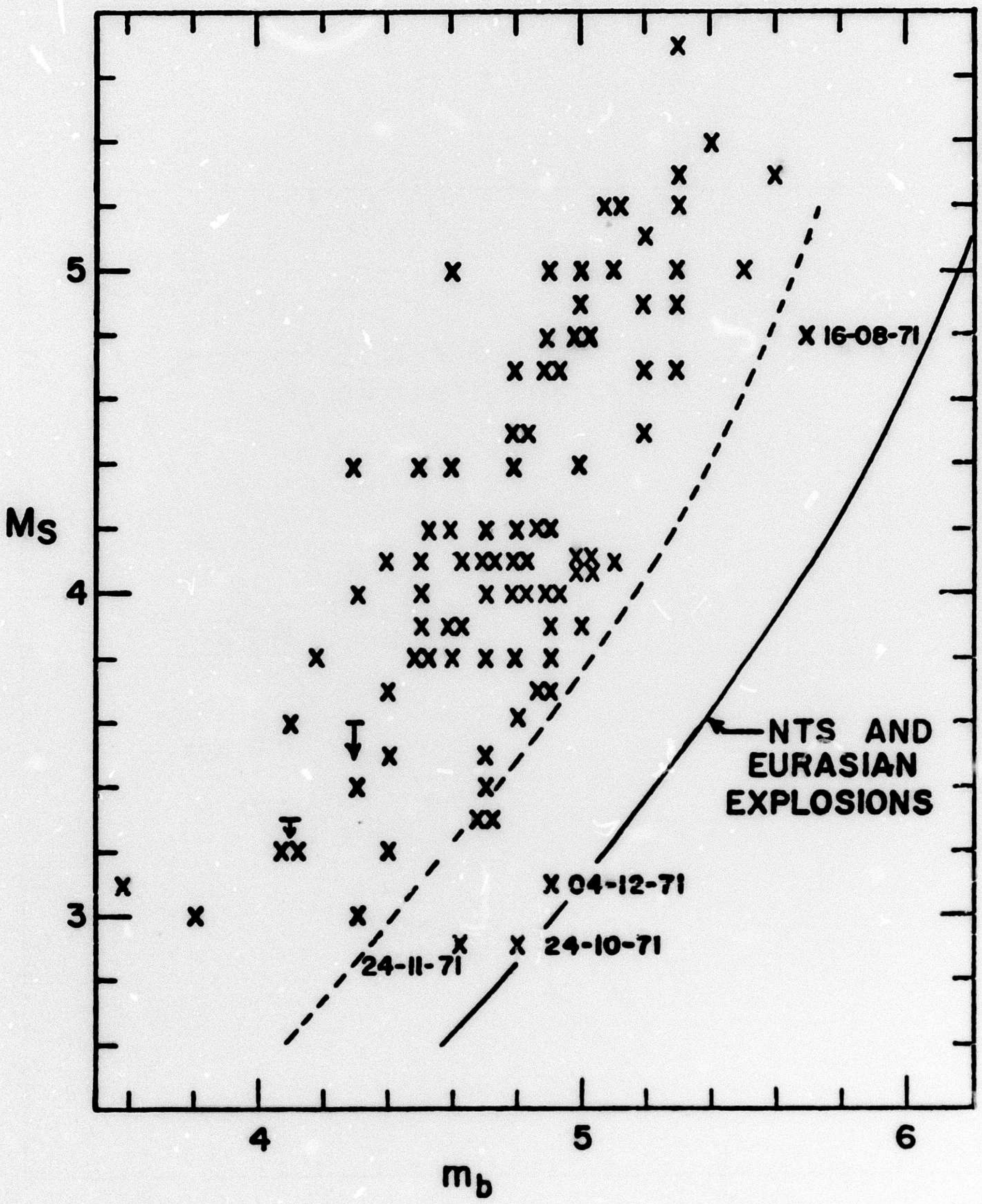

Figure 9. m_s:M_b values for Eurasian earthquakes. The dashed-line curve, obtained by displacing the explosion curve by 0.5 m_b units, is an envelope for most of the earthquakes.